Reference Frames, EOP, and Modeling VLBI Delays

David Gordon
NVI, Inc., NASA/GSFC

TOW Meeting, 2011-May-09

Three Components of Space Geodesy

- Terrestrial Reference Frame (TRF)
- Celestial Reference Frame (CRF)
- Earth Orientation Parameters (EOP)

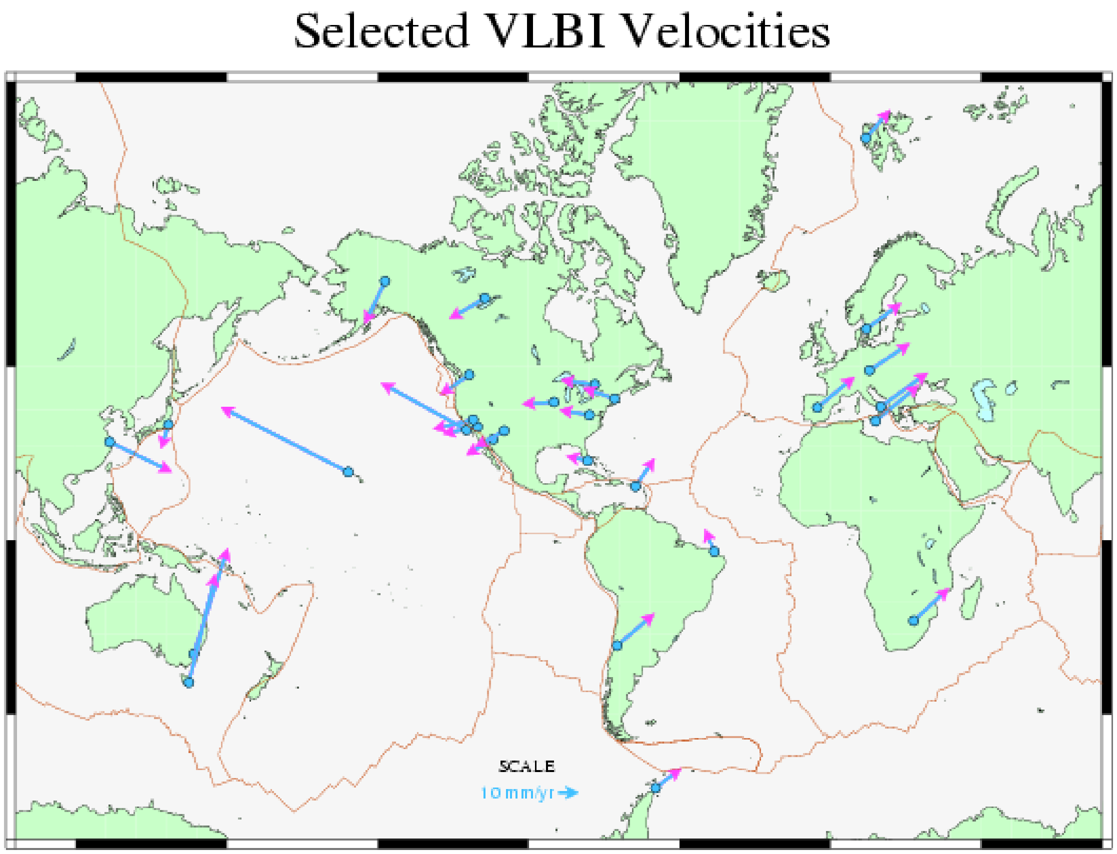
The Terrestrial and Celestial reference frames are tied together by the set of Earth orientation parameters.

Terrestrial Reference Frame

- Defines the positions and velocities of a set of reference sites over the Earth at a particular epoch.
- Current official TRF is ITRF2008. Epoch is 2005.0. Derived from VLBI, GPS, SLR, and DORIS contributions. Positions for 118 VLBI sites.
- Accounts for current plate tectonic motions, past earthquakes, rail repairs, etc.
- Does not account for earthquakes, etc, after 2008.0 (Chile, Japan). So we have to keep monitoring.

ITRF2008

- 934 stations at 580 sites.
- 463 sites in the northern hemisphere, 117 in the southern hemisphere.
- 84 co-location sites.
- For VLBI sites – intersection of axes.



NUVEL1A-NNR reference frame.

Earth Orientation Parameters

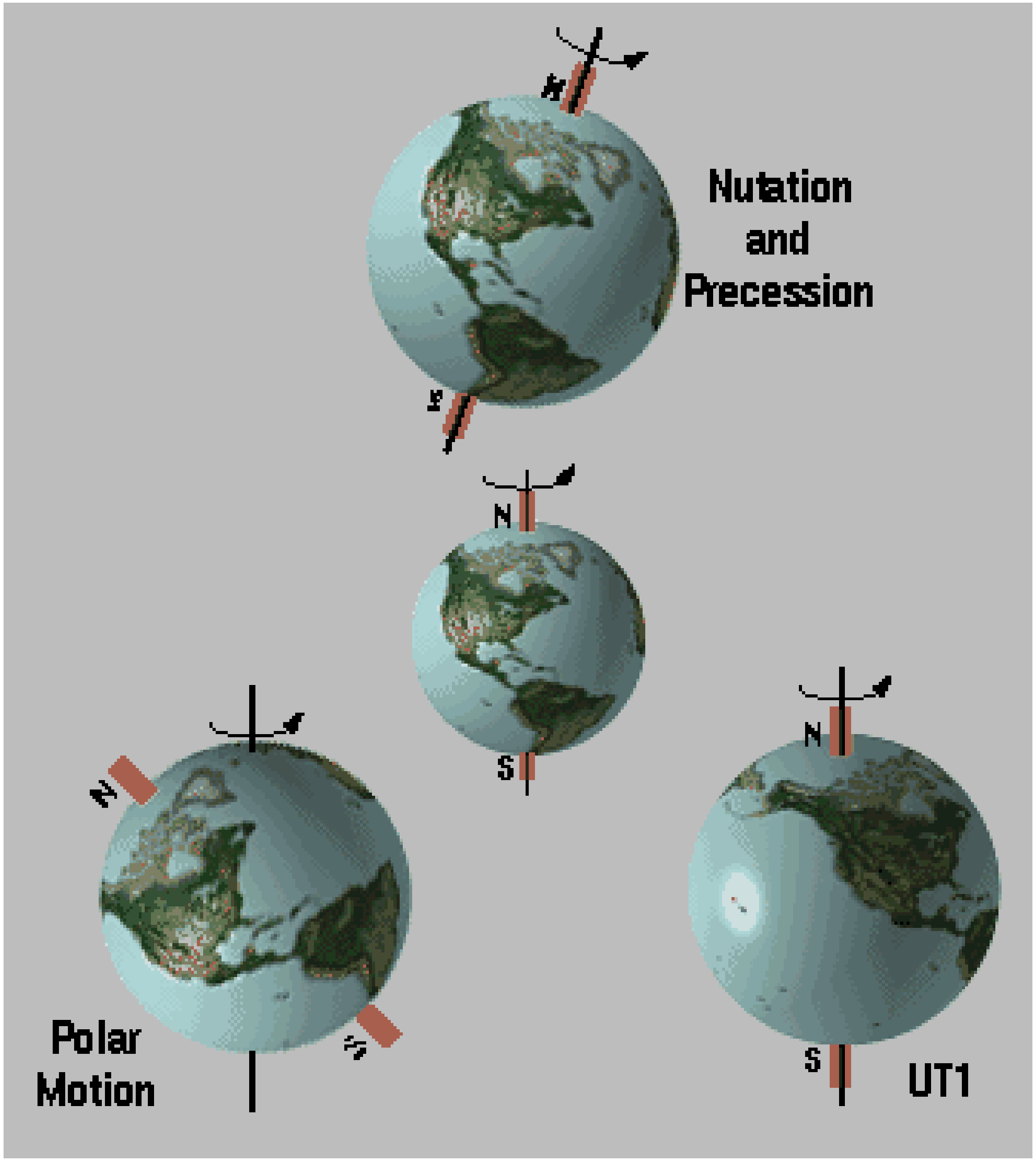
- 5 angles which give the orientation of the Earth w.r.t. the celestial reference frame.

  - X, Y pole position.

  - UT1-UTC (correction to UTC) or TAI-UT1.

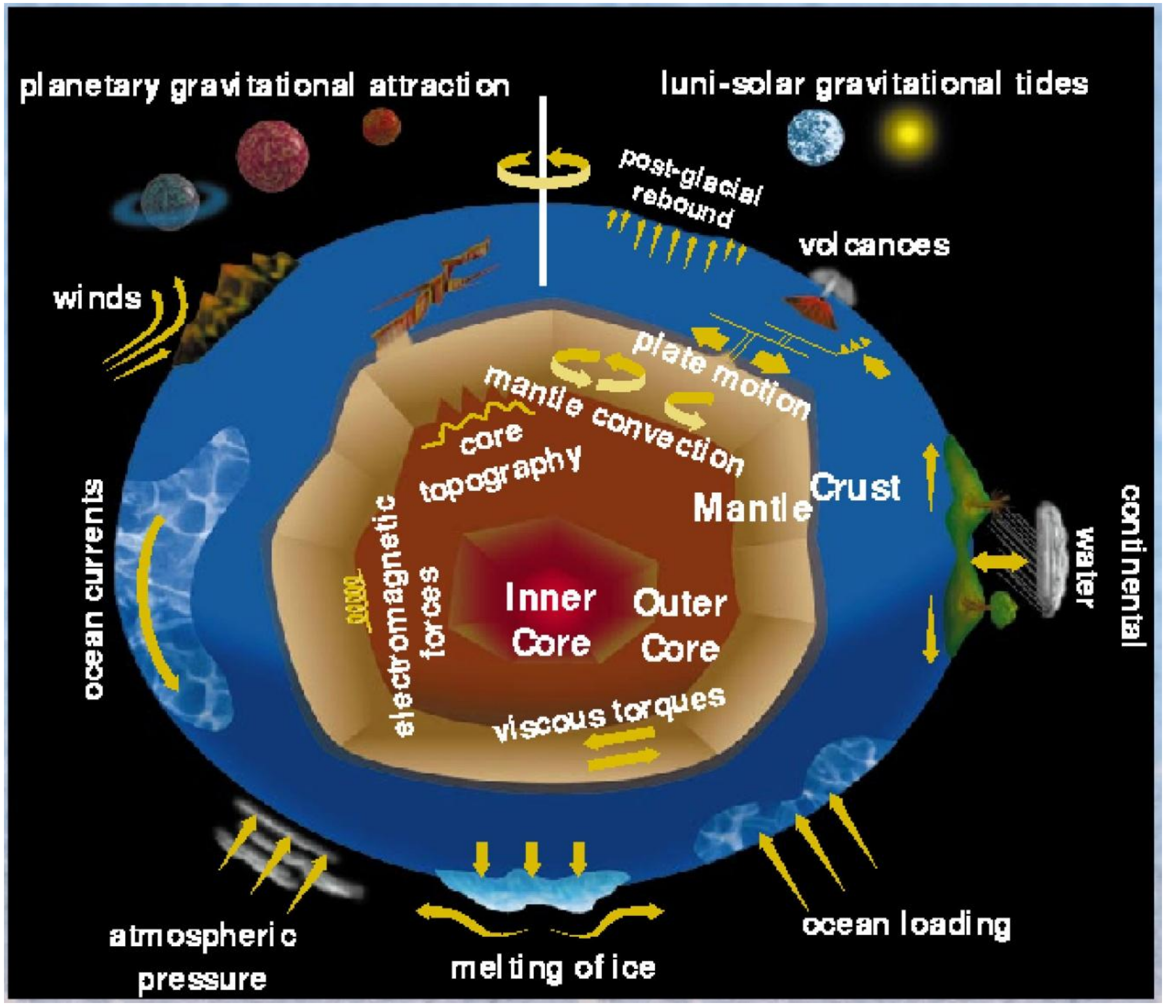
  - Nutation offsets from a standard model.

Usually given at 1.0 day intervals. Requires interpolation to get EOP at the desired epochs (time tags of the VLBI observations).


Nutation
and
Precession
N
S
Polar
Motion
UT1

Causes for Variations of the Earth’s Orientation

- Planetary gravitational attraction
- Winds
- Ocean Currents
- Atmospheric pressure
- Melting of Ice
- Ocean Loading
- Continental Water
- Volcanoes
- Post glacial rebound
- Lunar - solar gravitational tides
- Plate motion
- Mantle convection
- Core topography
- Electromagnetic forces
- Viscous torques



planetary gravitational attraction
luni-solar gravitational tides
post-glacial rebound
volcanoes
winds
plate motion
mantle convection
core topography
Crust
Mantle
ocean currents
electromagnetic forces
Inner Core
Outer Core
continental water
viscous torques
atmospheric pressure
melting of ice
ocean loading

Celestial Reference Frame

- A set of coordinates (RA and Dec) of ‘fixed’ distant objects (stars, galaxies, quasars, etc).
- First CRF’s were optical -- catalogs of star positions.
- In 1995, the first International Reference Frame (ICRF) of VLBI radio source positions was generated and became official Jan. 1, 1997.
- ICRF2 was generated in 2009 and became the official CRF on Jan. 1, 2010.

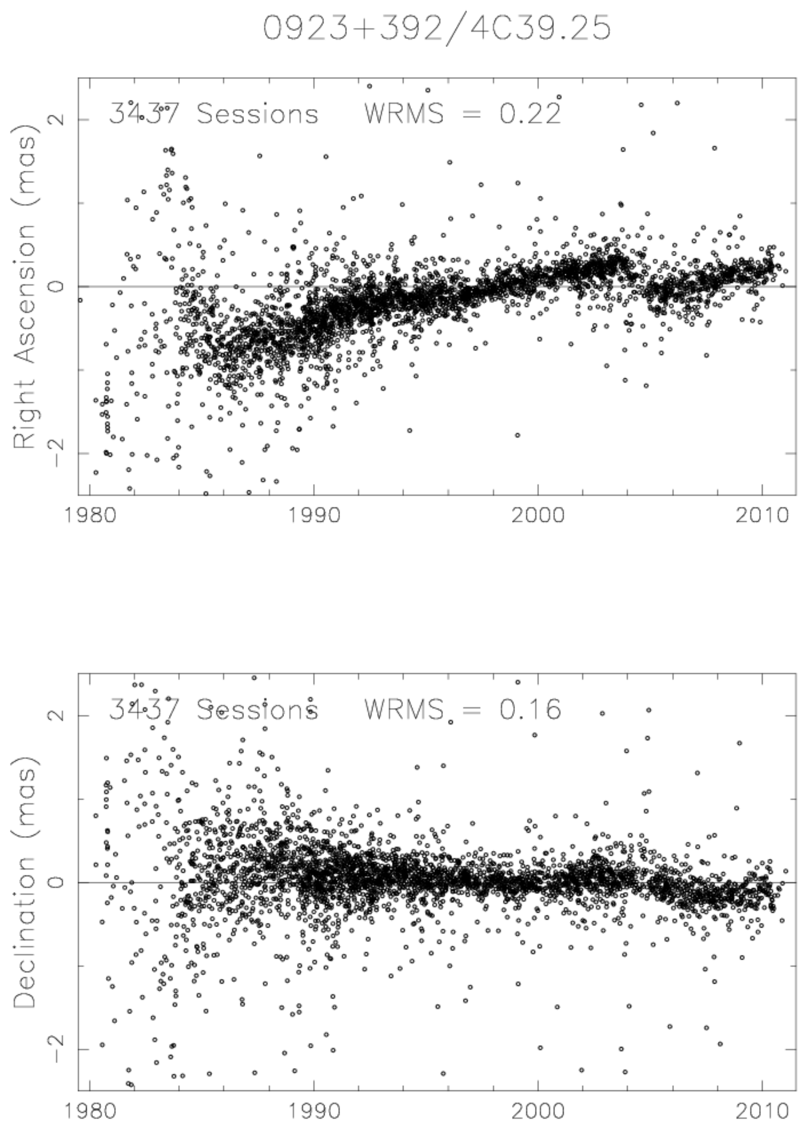
CRF Comparison

	ICRF (1995)	ICRF2 (2009)	Today (2011)
# VLBI Observations	~1.6 million	~6.5 million	~7.5 million
# Defining Sources	212	275	
# Total Sources	608	3414	3522/3673
Noise Floor	~250 μas	~40 μas	
Axis Stability	~20 μas	~10 μsec	

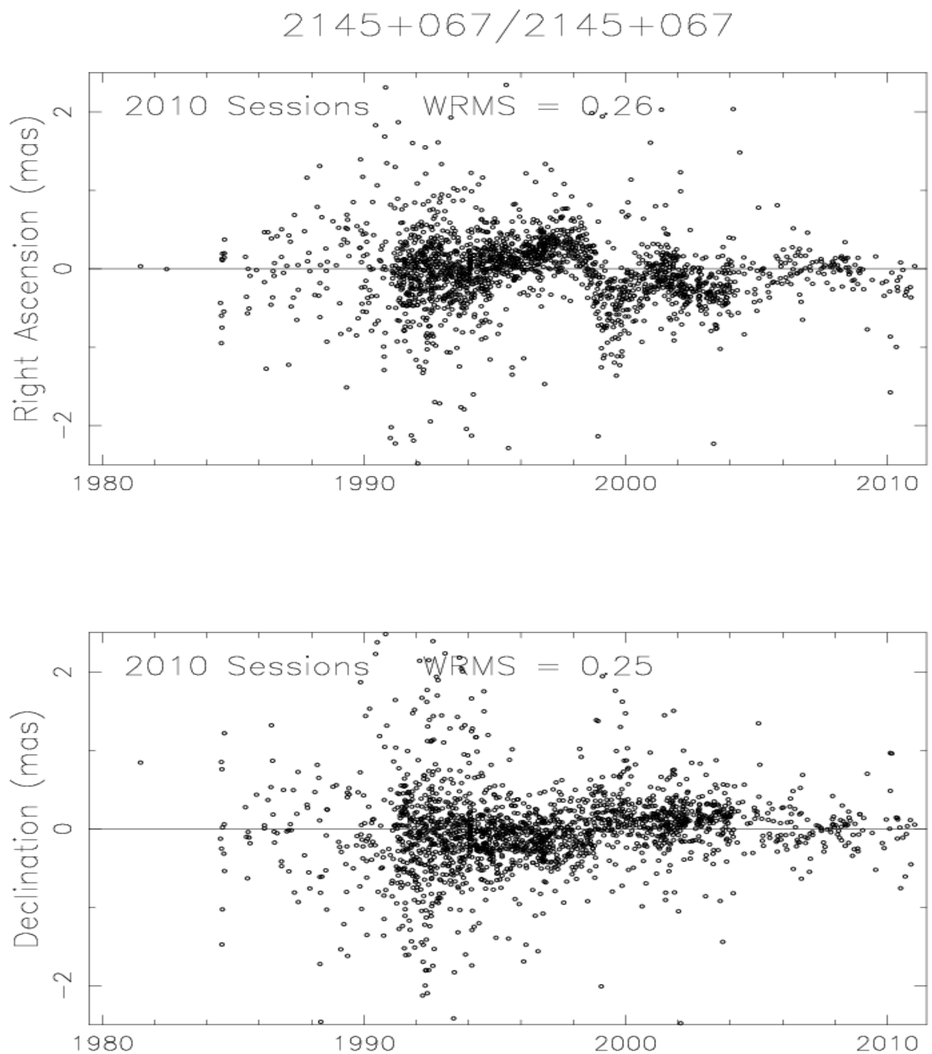
ICRF2

- First ICRF suffered from unstable ‘defining’ sources and uneven sky distribution of defining sources.
- The 295 ICRF2 defining sources were chosen based on historical stability, minimal source structure, and even sky distribution. Only 97 of the 212 ICRF defining sources were considered suitable as ICRF2 defining sources.
- 3414 total sources: 1448 observed multiple times, 1966 observed only once (mostly in VLBA Calibrator sessions).

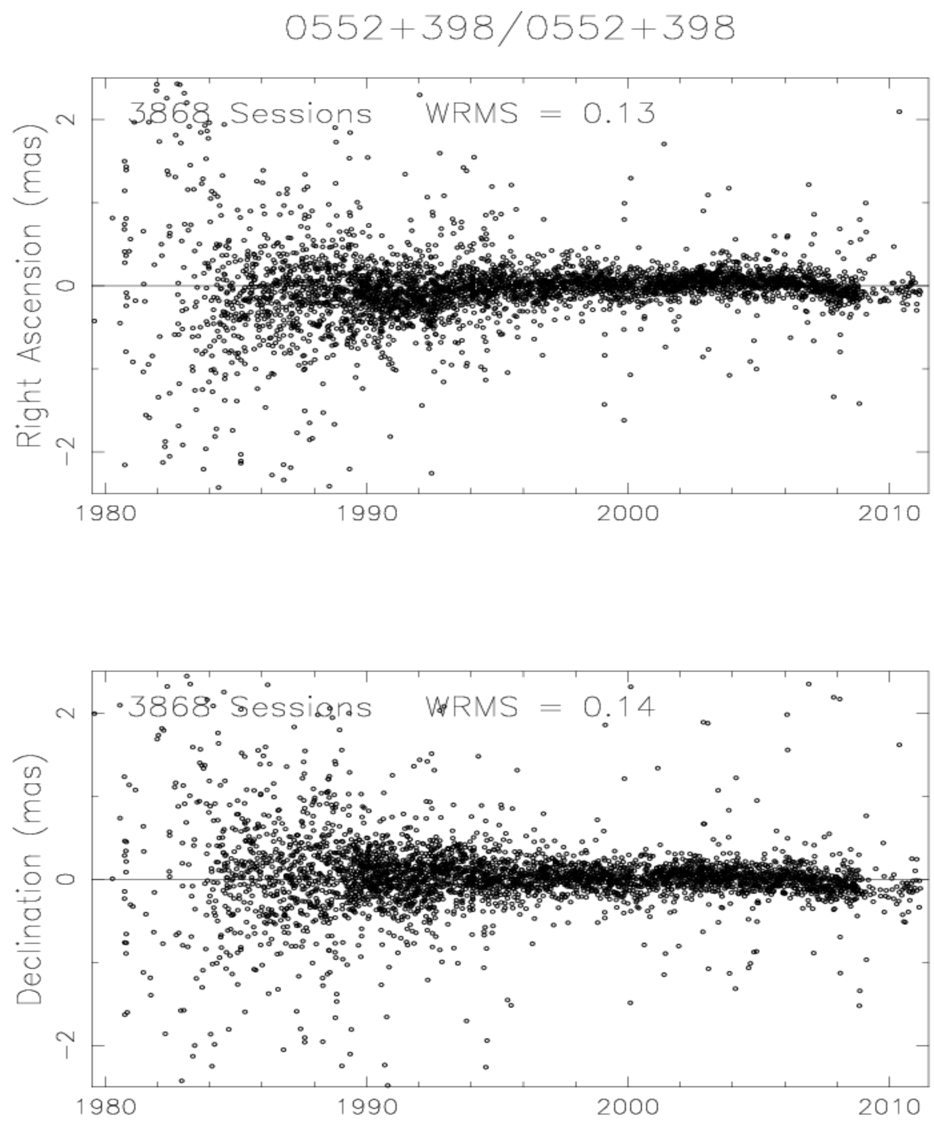
An Unstable Source



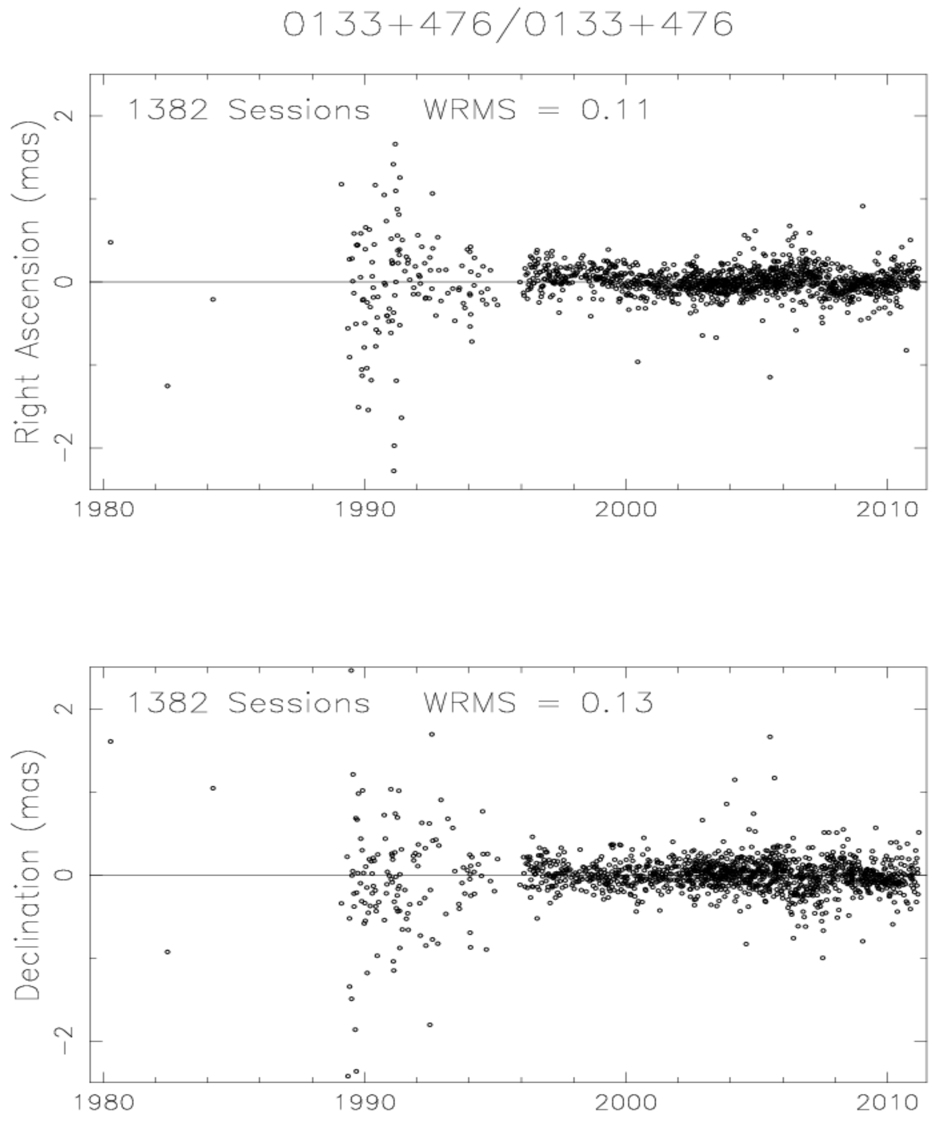
Unstable ICRF Defining Source



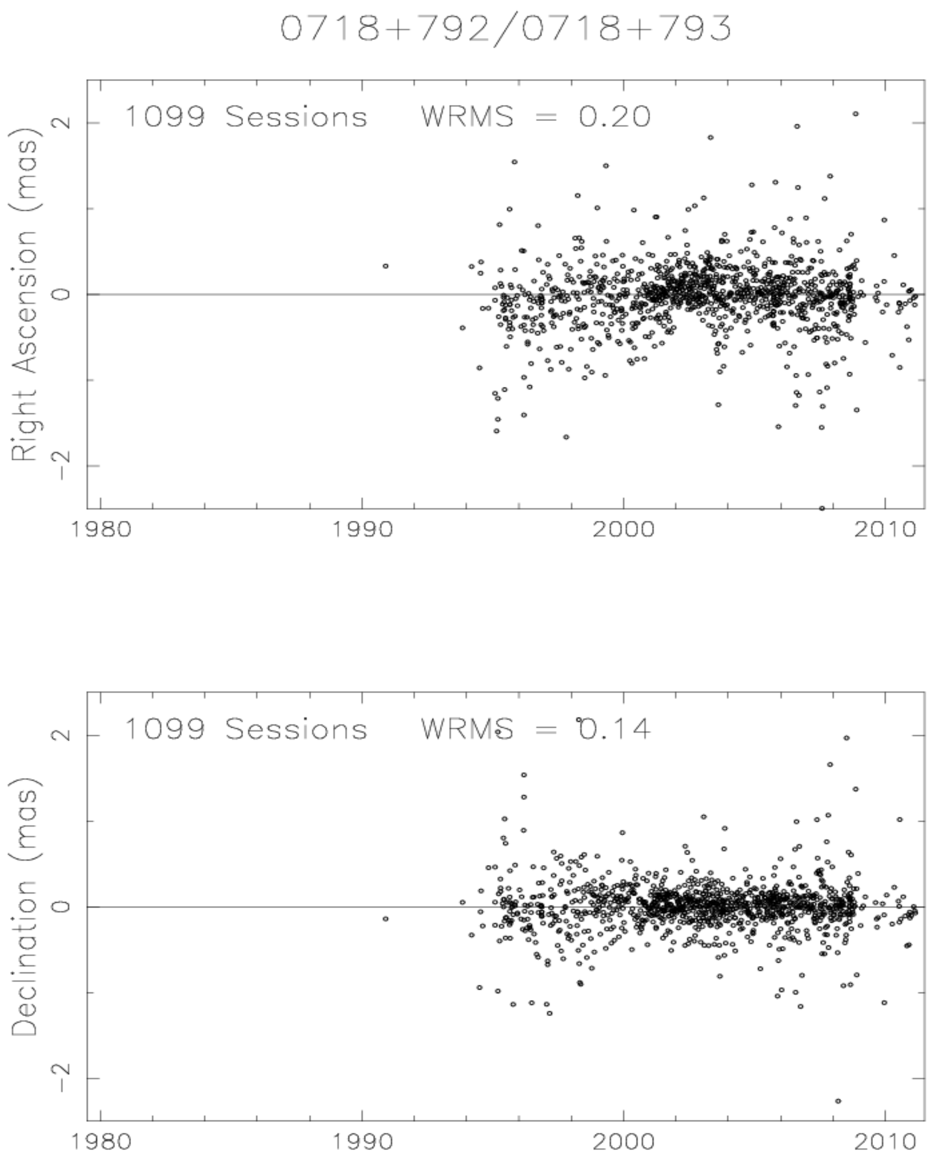
Stable ICRF2 Defining Source



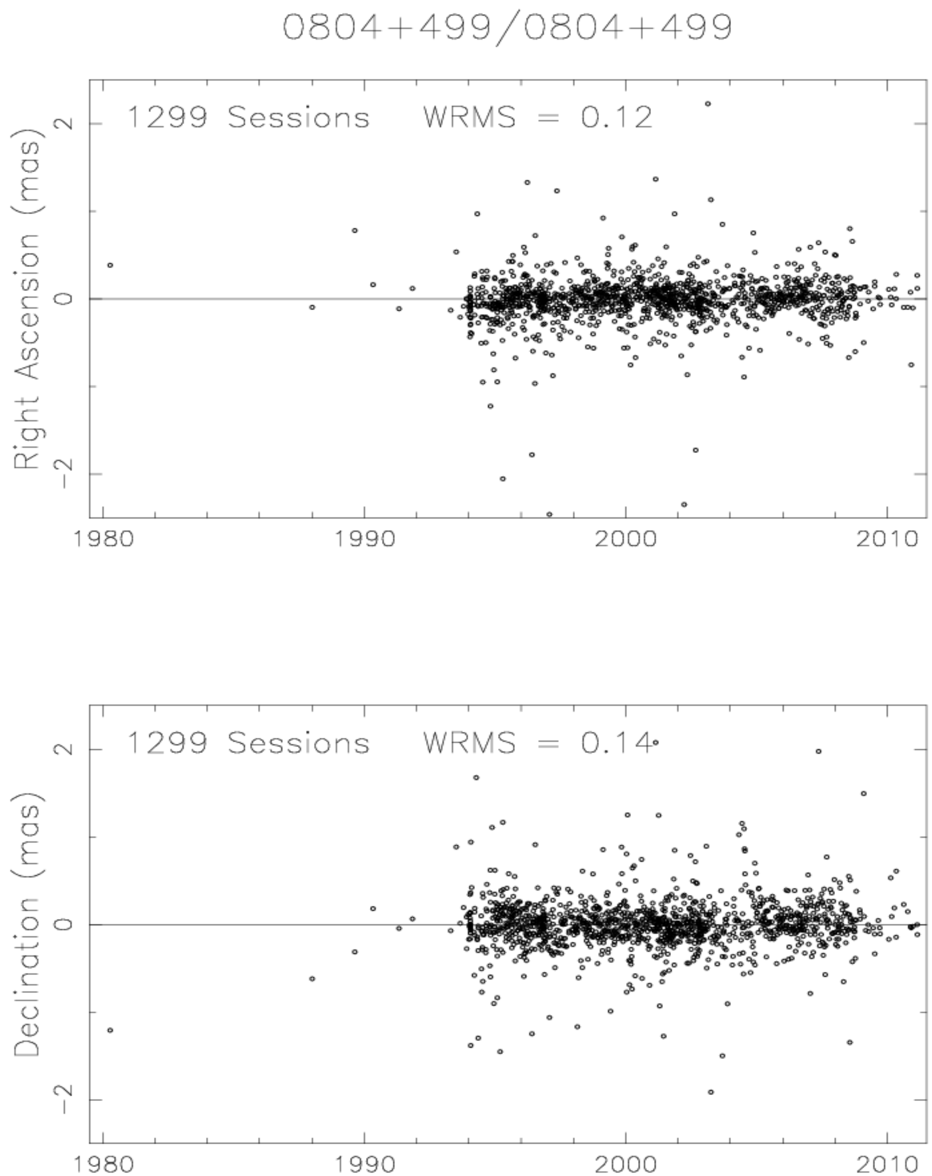
ICRF/ICRF2 Defining Source



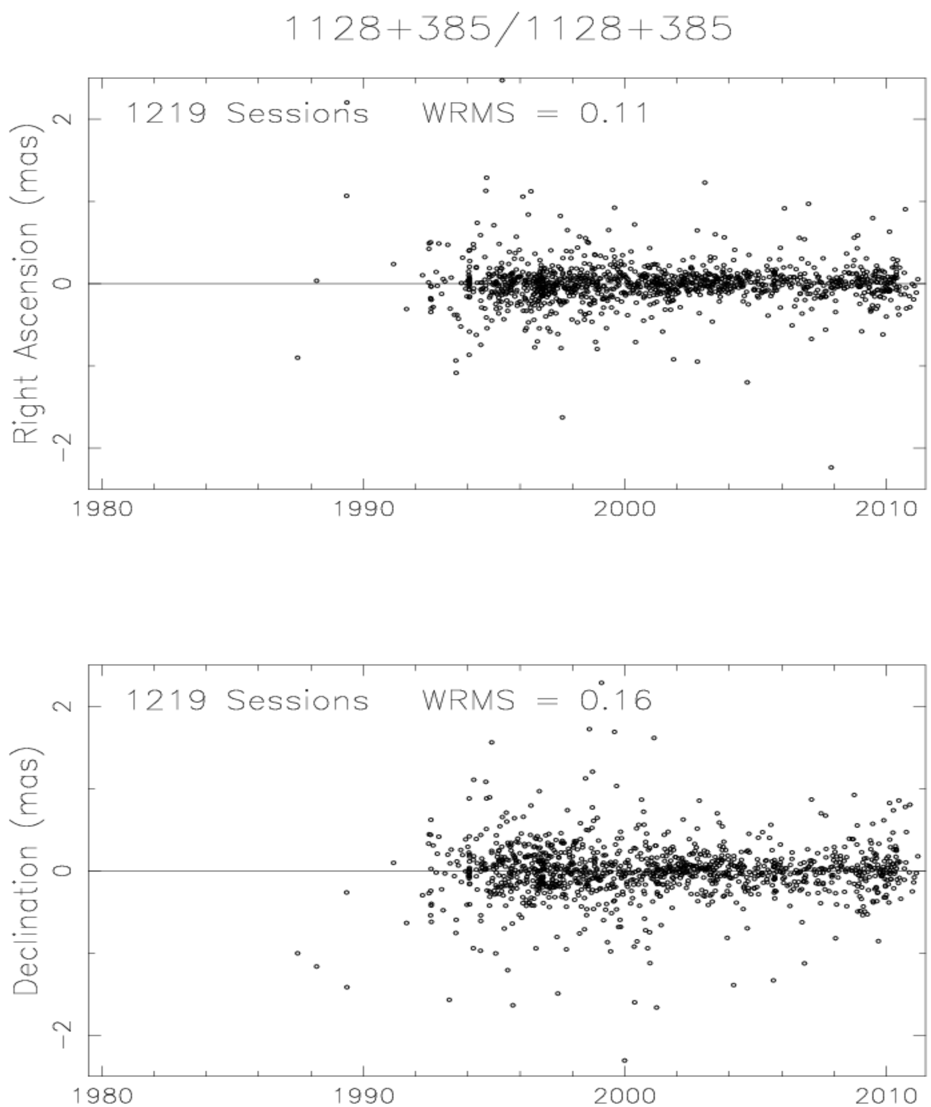
ICRF/ICRF2 Defining Source



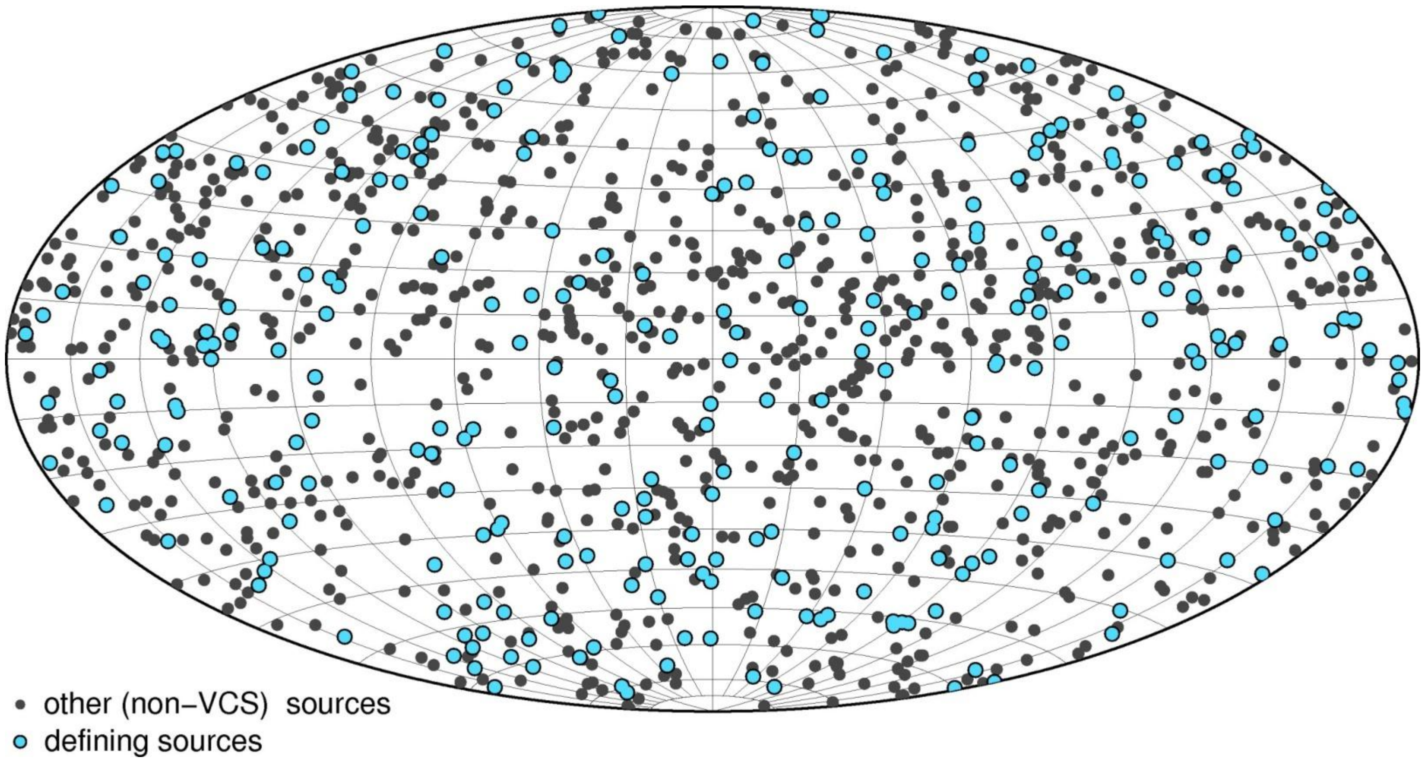
ICRF/ICRF2 Defining Source



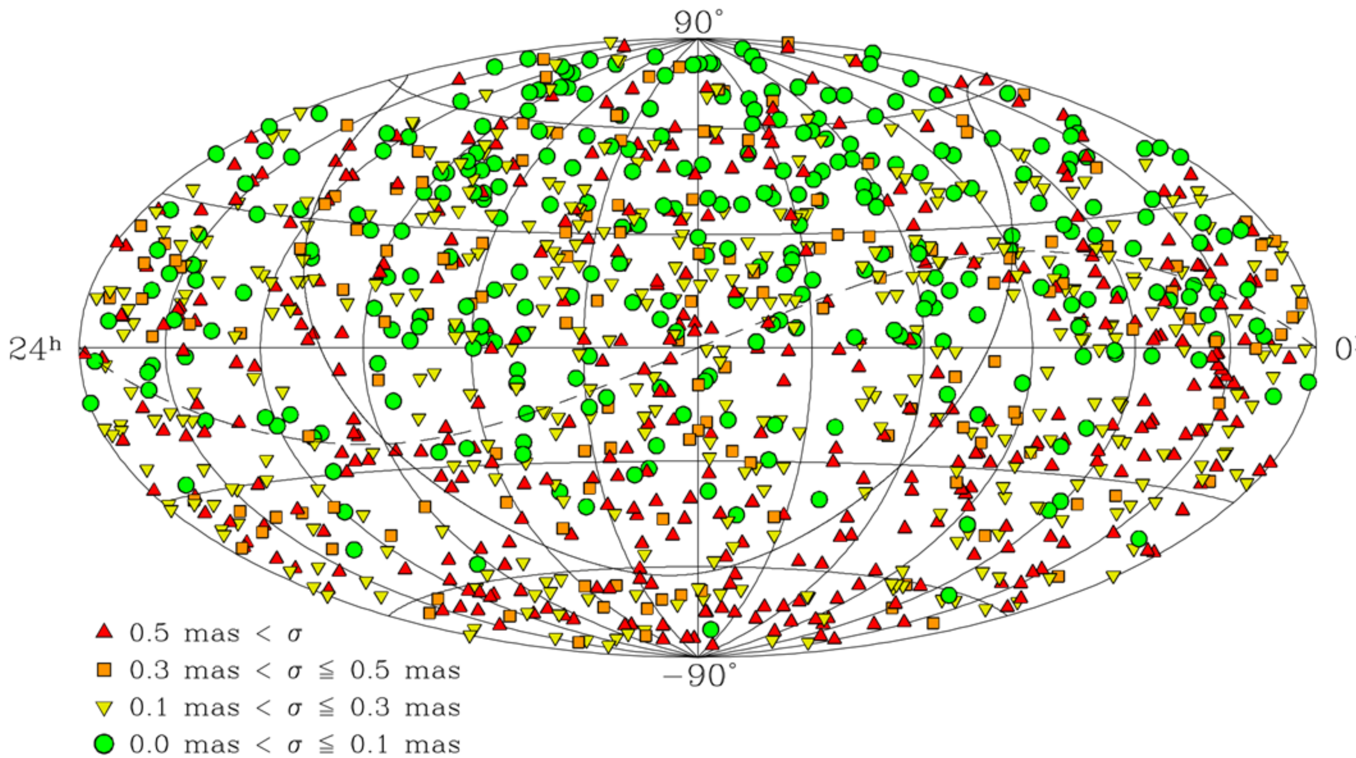
ICRF/ICRF2 Defining Source



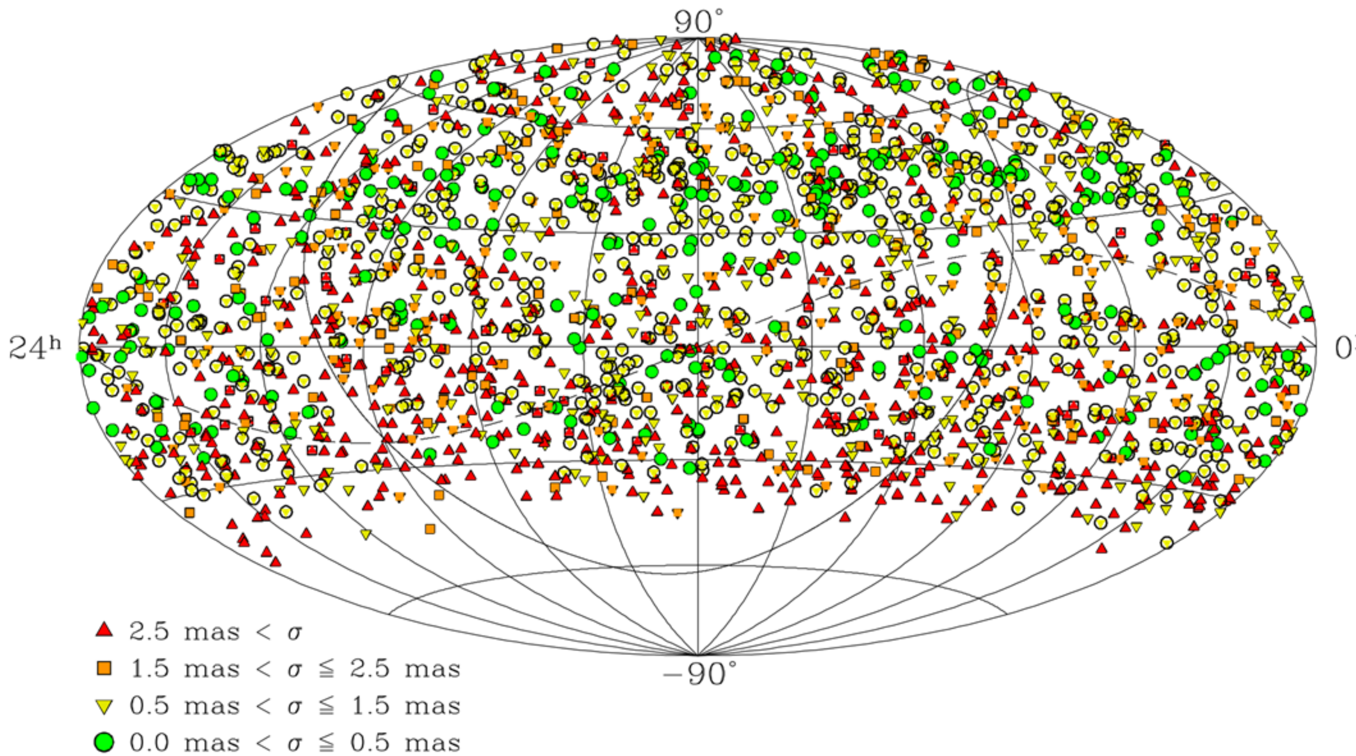
ICRF2: Multiple Session Sources



1217 ICRF2 Sources (Non-VCS)



2197 VCS-Only Sources



What will ICRF3 be?

VLBI or GAIA or combination VLBI/GAIA?

Will need to consider 'secular aberration drift'.

- Caused by our circular motion around the galactic center.
- Streaming motion of all extragalactic sources towards the galactic center at 4-6 μasec/yr for sources at the galactic poles.

There may be an ICRF2-ext in a few years.

Modeling VLBI Delays

How do we compute a theoretical VLBI delay?

- Needed in least squares solutions.
- Needed at the VLBI correlators.

This is what program Calc does.

Step 1

Treat Earth as a solid body. Compute a solid body rotation matrix to transform crust-fixed site positions into celestial reference frame positions.

Combine rotations due to precession, nutation, diurnal spin, and polar motion.

Precession/Nutation

Compute X, Y precession/nutation values using the IAU2000A/2006 model. Use these values to compute a precession/nutation rotation matrix and its first time derivative.

Polar Motion

Interpolate Xp, Yp polar motion to observation epoch. Do a spline fit using 15 tabular points.

Compute and add high frequency terms (due to ocean tides and short period nutation (libration)).

Use total Xp, Yp to compute a polar motion rotation matrix and its first time derivative.

Diurnal Spin

Convert from UTC to UT1. Compute the ‘Earth Rotation Angle’ (similar to Greenwich siderial time) at the UT1 epoch. Compute a diurnal spin matrix and its first and second time derivatives.

TRF-to-CRF Rotation Matrix

Combine the 3 matrices:

[TRF-to-CRF] = [Precession/Nutation] * [Diurnal Spin] * [Polar Motion]

Multiply site positions by [TRF-to-CRF] rotation matrix to get site positions in the CRF.

Step 2. Adjustments at each site

Elastic Effects:

- Solid Earth Tide (~12 hr period, few cm)
- Ocean Loading (~12 hr period, mm-cm)
- Pole Tide (~14 months, mm-cm)
- [Ocean Pole Tide Loading] – Not yet in Calc
- [Atmosphere Pressure Loading] – {in Solve}

Other Physical Offsets:

- Axis offset correction (cm-m)
- [Antenna thermal expansion/contraction (mm-cm)] – {in Solve}

Refractive Media Delays:

- Atmosphere delays (NMF) (nsecs) – {VMF in Solve}
- [Ionosphere delays] (hundreds of psec) {X/S or GPS in Solve}

Step 3. Combine all effects to get the baseline vector B, in the CRF (J2000.0)

- Add adjustments to each site position, get **X1** and **X2**.
- Compute baseline vector

  $$\mathbf{B} = \mathbf{X2} - \mathbf{X1}$$

  [At most correlators, station 1 is at the geocenter.]
- Compute source unit vector, **k**, from the source RA and Declination.

Step 4. Compute Theoretical Delay

Use the Eubanks 'Concensus' Model.

Basic equation is $\tau = -1/c\ (\mathbf{k} \cdot \mathbf{B})$, but

- Need to add gravitational deflection from sun, moon, Earth, other planets.
- Include relativistic and barycentric transformations.
- Add atmosphere delays
- Correlators also need to include clock offsets.

Partial Derivatives

- Calc also computes partial derivatives of the delay w.r.t.:

  -Xp, Yp, UT1, dX, dY, source position, site position, atmosphere, axis offset, etc.

Can solve for these during the least squares adjustment in Solve.